

# Colossal Paramagnetic Moment in Metallic Carbon Nanotori

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The search for carbon nanostructures with large magnetic moments has hitherto been explored unsuccessfully in  $C_{60}$ , graphite, and single-wall carbon nanotubes. Among the carbon structures explored thus far graphite has the largest diamagnetic moment of magnitude  $-0.03$  emu/g at 0.1 Tesla and at temperatures  $< 100$  K. However, in a recent theoretical study based on a  $\pi$ -orbital tight-binding theory (*Phys. Rev. Lett.* 88, 217206 (2002)), we have shown that metallic nanotubes bent into ring-shaped form referred as nano-tori, if they still remain in the metallic state, exhibit giant paramagnetic moments of magnitude  $\sim 30$  emu/g, which is thousand times larger than that of graphite ( $\sim 0.03$  emu/g). The physics underpinning the colossal paramagnetic moment has been shown to arise from the interplay between the toroidal geometry and the ballistic motion of electrons in the metallic nanotube.

The magnetic responses due to both metallic and semiconducting nanotori have been investigated. We found that there are two types of behavior associated with the metallic nanotori, corresponding to the two different types of metallic nanotubes from which they may be formed, with one type exhibiting large paramagnetic moments for any diameter, while the other exhibiting large paramagnetic moments for only selected "diameters". The existence or non-existence of magic diameters for nanotori possessing giant paramagnetism depends on the metallicity condition satisfied by nanotori, namely, the electron wave (with the Fermi wave length) must be accommodated along the circumference ( $\ell$ ) of the nanotorus. This leads to, where  $\ell$  is the translational vector of the tube, and  $m$  and  $n$  are integers. For nanotori formed from metallic nanotubes with the Fermi vector occurring at or (metal-1 nanotubes), the metallic condition requires which can be satisfied for nanotori with any diameter. On the other hand, for nanotori formed from metallic nanotubes with or (metal-2 nanotubes), the metallic condition requires, which can be satisfied by nanotori of only selected diameters.

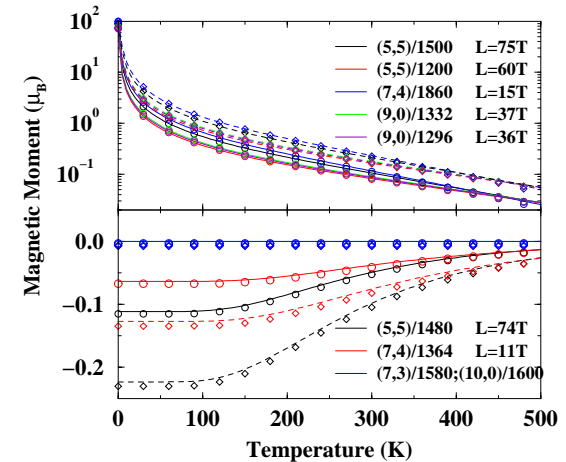
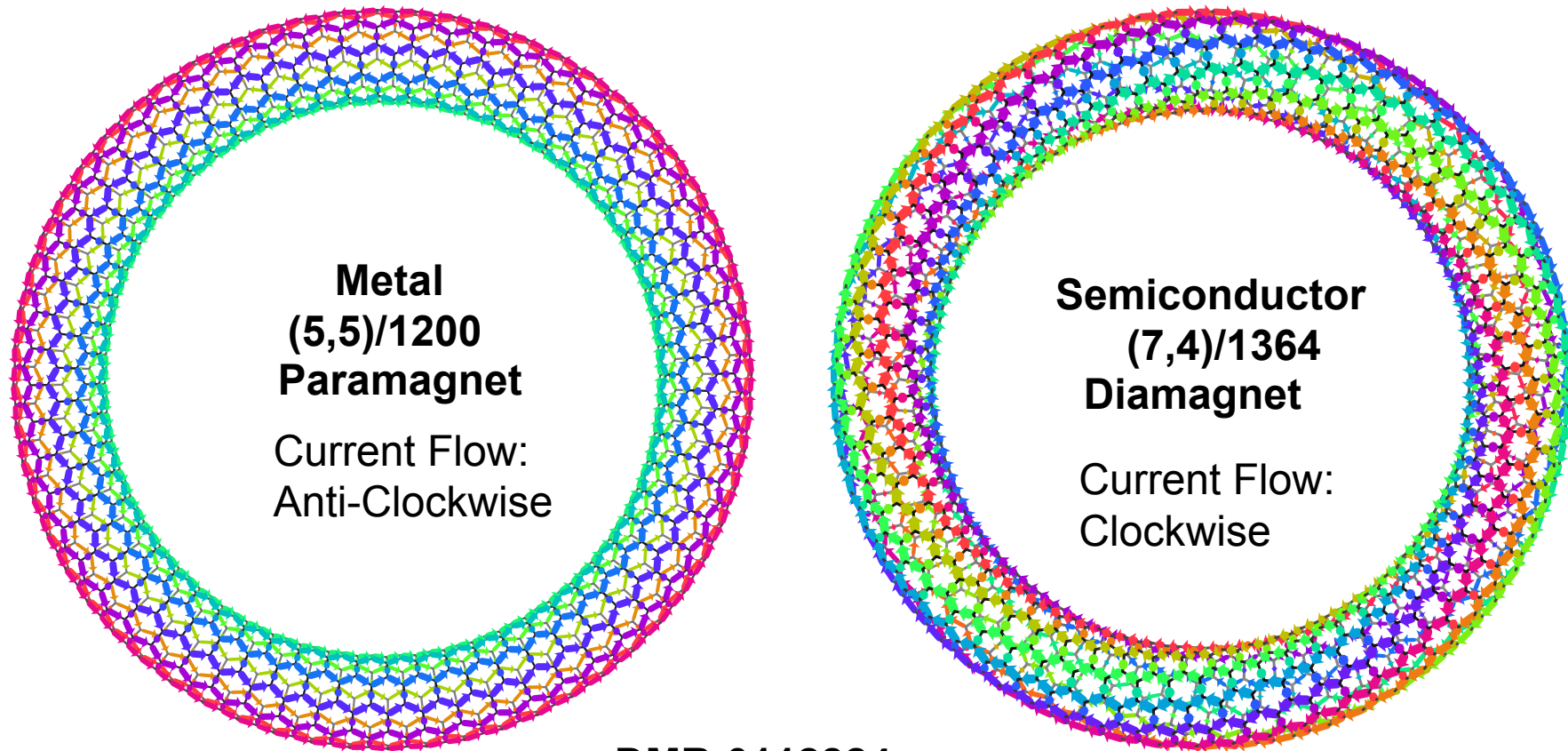


Fig. 1 shows the paramagnetic and diamagnetic behaviors of metal and semiconductor nanotori respectively. It is seen that the metal nanotori have very large paramagnetic moments at low-temperatures with a very strong temperature-dependence (upper panel). The diamagnetic responses of semiconducting nanotori show two types of behaviors (lower panel) with one type showing a mild temperature-dependence while the other one no temperature-dependence, corresponding to semiconducting nanotori formed from metallic nanotubes and those formed from semiconducting nanotubes, respectively.

In summary, it is found that an insignificantly small magnetic field is able to align the magnetic moments of metallic nanotori in the direction of the field and produce giant magnetic moments. Our finding has the potential for developing new types of magnetic storage devices, switching devices, etc. Experimental verification of our finding is currently undertaken by Dr. Bruce Alphenaar of University of Louisville (Electrical Engineering) and Dr. J. Liu of Duke University (Chemistry Department). The present work also involves collaboration with Dr. G.Y. Guo of National Taiwan University.

# Ring Currents in Carbon Nanotori

Fig. 2 shows the ring currents in a metallic and a semiconducting nanotorus respectively for a magnetic field pointing in the outward direction to the plane of the paper. Note that for a metallic nanotorus, the magnetic moment points in the same direction as the magnetic field consistent with the direction of the current flow. This situation is reversed for the case of a semiconducting nanotorus.



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